PB89-118368

# Continuous Measurement of Diesel Particulate Emissions (Journal Version)

(U.S.) Environmental Protection Agency
Research Triangle Park, NC

1988

U.S. Department of Commerce
National Technical Information Service
NTIS

**TECHNICAL REPORT DATA**
*(Please read Instructions on the reverse before complet*

| | | |
|---|---|---|
| 1. REPORT NO. EPA/600/J-88/161 | 2. | 3. PB89-118368 |
| 4. TITLE AND SUBTITLE<br>CONTINUOUS MEASUREMENT OF DIESEL PARTICULATE EMISSIONS (Journal Version) | | 5. REPORT DATE 1988<br>6. PERFORMING ORGANIZATION CODE |
| 7. AUTHOR(S)<br>Soyoung Cha, Univ. of Illinois, Chicago, IL<br>F. Black and F. King, U.S. EPA, RTP, NC 27711 | | 8. PERFORMING ORGANIZATION REPORT NO. |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Atmospheric Sciences Research Laboratory<br>Office of Research and Development<br>U.S. Environmental Protection Agency<br>Research Triangle Park, N.C. 27711 | | 10. PROGRAM ELEMENT NO. A101/D/74/02-3080 (FY-87)<br>11. CONTRACT/GRANT NO. |
| 12. SPONSORING AGENCY NAME AND ADDRESS<br>Atmospheric Sciences Research Laboratory - RTP, NC<br>Office of Research and Development<br>U.S. Environmental Protection Agency<br>Research Triangle Park, N.C. 27711 | | 13. TYPE OF REPORT AND PERIOD COVERED<br>14. SPONSORING AGENCY CODE EPA/600/09 |
| 15. SUPPLEMENTARY NOTES<br>JAPCA, 38(3):252-257, July 1988 | | |

16. ABSTRACT

Evaluation of emerging diesel particulate emissions control technology will require analytical procedures capable of continuous or "real-time" measurement of transient organic and elemental carbon emissions. Procedures based on the flame ionization properties of organic carbon and the opacity or light extinction properties of elemental carbon are described. The described instrumentation provided adequate time resolution to observe the transient concentrations associated with typical automobile driving patterns. Accuracy and precision are evaluated by comparing integrated average results to measurements using classical gravimetric filtration techniques. Emissions from two diesel passenger cars with substantially different chemical compositions are examined. Mass specific extinction coefficients are developed using the Beer-Lambert Law and a simplified linear model which proved adequate for particulate concentrations typical of diluted passenger car exhaust.

(Copyright (c) APCA 1988.)

17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| | | |

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL INFORMATION SERVICE
SPRINGFIELD, VA. 22161

| 18. DISTRIBUTION STATEMENT | 19. SECURITY CLASS (This Report) | 21. NO. OF PAGES |
|---|---|---|
| RELEASE TO PUBLIC | UNCLASSIFIED | 9 |
| | 20. SECURITY CLASS (This page) UNCLASSIFIED | 22. PRICE |

*JAPCA* 38: 252-257 (1988) Reprinted from APCA Journal, Vol. 38, No. 3, July 1988

EPA/600/J-88/161
JOURNAL ARTICLE

# Continuous Measurement of Diesel Particulate Emissions

**Soyoung Cha**
University of Illinois at Chicago
Chicago, Illinois

**Frank Black and Foy King**
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina

**Evaluation of emerging diesel particulate emissions control technology will require analytical procedures capable of continuous or "real-time" measurement of transient organic and elemental carbon emissions. Procedures based on the flame ionization properties of organic carbon and the opacity or light extinction properties of elemental carbon are described, and applied for measurement of particulate emissions from diesel engines. The instrumentation provided adequate sensitivity and time resolution for observation of the transient emissions associated with typical automobile urban driving conditions. Analytical accuracy is evaluated by comparing integrated average results to measurements using classical gravimetric filtration and solvent extraction procedures. Mass specific extinction coefficients are evaluated using the Beer-Lambert law. A simplified linear model relating elemental carbon concentration to opacity is also evaluated.**

Diesel engines, widely used in heavy-duty trucks and buses in the United States, pose environmental problems related to particulate emissions and noise. During the period 1980 to 1985, the U.S. Environmental Protection Agency (EPA) promulgated regulations for reduction of particulate emissions from diesel passenger cars, trucks, and buses.[1-3] As a consequence, many future diesel motor vehicles will use some form of exhaust after-treatment to reduce particulate emissions. Prototype diesel particulate control systems have relied upon "trap-oxidizer" concepts whereby the particulate emissions are filtered or trapped from the exhaust stream, and subsequently oxidized or burned before tailpipe backpressures influence engine performance.[4-6] During burn-off, the trap is regenerated by oxidizing the carbon particulate to $CO_2$. Regenerative temperatures are normally achieved by locating the trap close to the engine exhaust ports or by using either catalytic fuel additives or catalytic trap coatings to lower the carbon ignition temperature.

Diesel particulate emissions are composed primarily of elemental carbon ($C_e$) and organic carbon ($C_o$). Other components, including sulfate and various metal oxides, typically constitute less than 5 percent of the total mass.[7] Adsorption and condensation are temperature and concentration dependent physical processes by which diesel $C_o$ emissions become associated with the particulate phase.[8] Normally this association occurs while the exhaust is cooling in the tailpipe and immediately after leaving the tailpipe where rapid dilution and cooling occur. There are uncertainties about how trap-oxidizers will impact $C_o$ emissions during transient engine operation. There are also questions about possible elevated sulfate emissions with these control devices, especially during trap regeneration. Since emission characteristics are transient during normal engine operation, study of such uncertainty is very difficult without analytical tools capable of continuous or "real-time" measurement of the particulate emissions.

Conventional filter sampling, measuring an integrated quantity, cannot detect time-resolved transient emissions. However, several analytical procedures have been developed for this purpose. Optical instruments based on the relationship between particulate concentration and light scattering and/or absorption have been described.[9-14] Reasonable correlation between light absorption/extinction and $C_e$ concentration has been demonstrated with several of these instruments. The tapered element oscillating microbalance has been successfully applied for real time measurement of transient total particulate emissions.[15,16] Clerc and Johnson have demonstrated the use of predictive models for real-time estimation of $C_o$ concentrations.[17] Thus far, procedures for selective real-time direct measurement of particulate phase organic carbon have not been described.

Because organic adsorption and condensation are temperature and concentration dependent processes, observed diesel particulate emission rates can be sensitive to sampling procedures.[8] Recognizing the practical engineering limitations for laboratory simulation of the roadway exhaust dilution process, the EPA chose a tunnel dilution process for particulate emissions determination whereby the engine exhaust is mixed with filtered ambient air and diluted so that sample temperatures do not exceed 52°C during transient engine operation.[1,2] Total hydrocarbon emissions (THC), i.e., gas phase and particulate phase, are determined by heating the diluted exhaust sample to 190°C and measuring the level of organic carbon with a flame ionization detector (FID), which is selective for CH. This paper will describe a continuous particulate phase $C_o$ analytical procedure based on these definitions of organic emissions, and a continuous $C_e$ procedure based on optical opacity.

## Experimental Setup, Procedures, and Results

### Organic Carbon Analysis

As previously discussed, particulate phase $C_o$ is defined in the EPA certification practice as the organic mass filtered from a diluted exhaust stream at or below 52°C. Figure 1 illustrates a matched differential hot FID approach for continuous measurement of particulate $C_o$ by this definition. Channel A measures diluted total organic emissions sampled at 190°C and channel B diluted total organic emissions sampled at or below 52°C. The difference signal of the FIDs is then proportional to the particulate phase organic emissions.

Soyoung Cha is with the University of Illinois at Chicago. Frank Black and Foy King are with the Mobile Source Emissions Research Branch, Emissions Measurement and Characterization Division, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711. This paper was submitted for peer review March 6, 1987; the revised manuscript was received November 25, 1987.

Copyright 1988—APCA



NTIS is authorized to reproduce and sell this report. Permission for further reproduction must be obtained from the copyright owner.

For this approach to be functional, the two analytical channels should give equivalent response when there is no particulate phase organic matter in the sample. As an indication of this performance, transient injections of propane into the exhaust dilution tunnel were observed, and the integrated instrument responses found to be equivalent within ±1 percent. To further illustrate the performance of the system with little or no particulate phase organic, the dilute exhaust of a late model unleaded gasoline catalyst equipped vehicle was examined during the first six minutes of a cold start urban dynamometer driving simulation (federal test procedure).[18] The emissions are very low beyond six minutes. The results are shown in Figure 2. Also illustrated in Figure 2 is the system response to diesel exhaust over the same driving simulation. Particulate phase organic emissions were indicated over the entire sampling period with the diesel. This system is capable of accurately following the transient concentrations associated with urban driving simulations. FID fuel, sample, and scavenger air flow rates must be carefully matched to assure that differences due to hydrocarbon com-

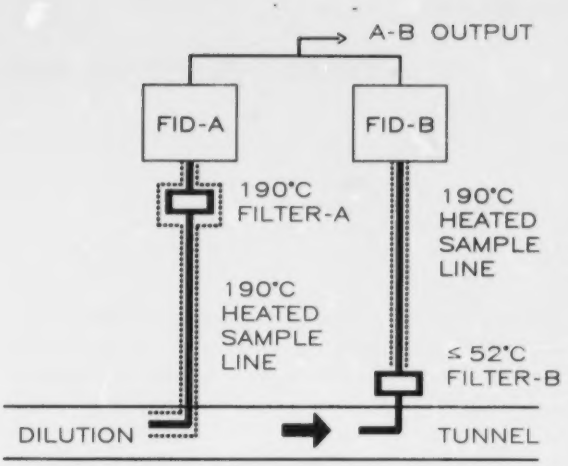


**Figure 1.** Hot FID procedure for particulate phase organic carbon.

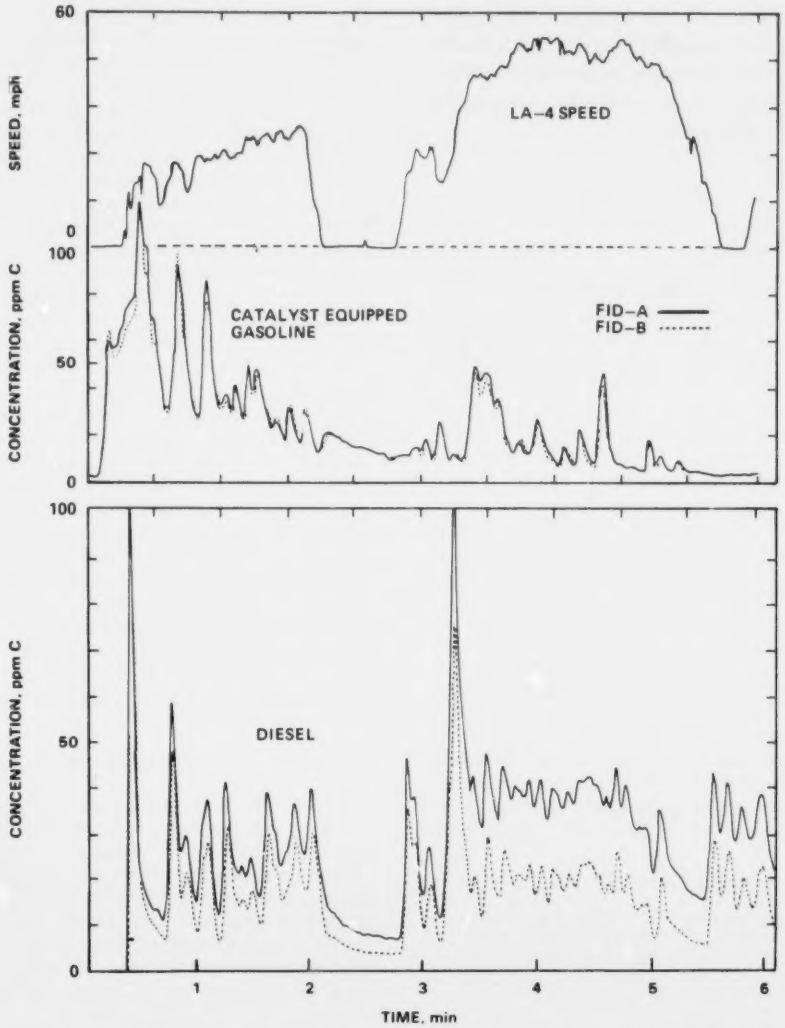


**Figure 2.** Matched FID response to catalyst equipped gasoline engine organic emissions and diesel engine organic emissions.

**Table I.** Particulate phase organic emissions (g/mi): FID versus gravimetric solvent extraction.[a]

| $A_f$ | $A_g$ | $B_f$ | $B_g$ | $A_f - B_f$ | $B_g - A_g$ |
|---|---|---|---|---|---|
| 0.65 ±0.04 | 0.034 ±0.022 | 0.44 ±0.04 | 0.309 ±0.109 | 0.21 ±0.03 | 0.271 ±0.088 |

[a] $A_f$, $B_f$: emission rates of organic matter detected by FIDs in Figure 1. $A_g$, $B_g$: emission rates of organic matter determined by soxhlet extraction of filters in Figure 1.

pound response variations resulting from oxygen synergism are minimized.[19]

Table I presents results obtained with a diesel passenger car. The mass emission rates of organic matter, $A_f$ and $B_f$, were calculated using integrated concentrations measured by the A and B FID instruments and assuming an average hydrogen to carbon ratio of 2.12 (heptadecane). The difference $A_f - B_f$ is indicative of $C_o$ mass. To permit comparison with classical gravimetric procedures, filters A and B were soxhlet extracted with methylene chloride solvent and extracted mass emission rates reported as $A_g$ and $B_g$. The difference $B_g - A_g$ should be comparable to $A_f - B_f$. The observed ratio of FID particulate phase organic mass ($A_f - B_f$) to solvent extracted mass ($B_g - A_g$) is 0.77. This ratio is similar to the value 0.70 observed by Japar *et al.* who compared the thermal-optical analysis of particulate $C_o$ mass to toluene/propanol solvent extracted mass.[20] The small difference could be accounted for by more efficient extraction of polar compounds by Japar's solvent system and the hydrogen mass assumed in the FID calculations. These ratios are not considered unreasonable due to the presence of oxygen and extractable inorganic mass in the deposited particulate.[21]

### Elemental Carbon Analysis

Light absorption or extinction properties have served as convenient means for instantaneous measurement of diesel particulate emissions. Two typical instruments are the opacimeter and photoacoustic spectrophone. The opacimeter is less sensitive; however, it is cheaper and easier to operate than the photoacoustic spectrophone. In this study a unique long-path opacimeter was examined offering adequate pathlength (sensitivity) for measurement of diluted auto exhaust and adequate time response for following the transience of urban driving conditions.

The opacimeter operates on the principle of the Beer-Lambert law.

$$P = 100\ (1-e^{-A_eML}) \qquad (1)$$

where $P$: opacity, %,
$A_e$: mass specific extinction coefficient, $m^2/g$,
$M$: mass concentration, $g/m^3$,
$L$: optical pathlength, m.

This model is appropriate only when $A_e$ remains constant during a test. The product $A_eM$ is called the extinction coefficient $B_e$. $A_e$ represents particle extinction cross section per unit mass. It depends on a number of factors such as size distribution, particle shape, refractive index, and wavelength of probing light. There is substantial data relating opacity $P$ to diesel particulate mass concentration.[9-14] Diesel particles vary widely in chemical and physical properties. The size ranges from very small single particles of 0.01 μm to long chainlike agglomerates with dimensions of 0.1 to 0.2 μm.[22,23] Hence, the relationship $M$ versus $P$, being complex, needs further investigation to better define accuracy and precision. A simple calculation based on the Mie theory[24] of single carbon spheres cannot adequately account for light extinction behavior with diesel particles.

The opacimeter used in this study, a modified Celesco Model 107, operated over an optical path of 0.84 m. The increased optical pathlength provided sufficient sensitivity for measurements of diluted exhaust. It employed a light-emitting diode with an emission wavelength that peaked at 0.57 μm and silicon photodiode detector. The source and detector were mounted on three-axis rotation stages for precise alignment. Figure 3 is a schematic of the opacimeter. Initially, with all lines closed and exit lines operating one at a time, the control valves were adjusted to match the sample flow rates for both sides. With all lines open, both-side clean-

**Table II.** Summary of opacity and filter measurements.

| Opacity (%) | Mass concentration ($mg/m^3$) Total particulate | SOF | $C_e$ | % SOF | $A_e$($m^2/g$) $A_{et}$[a] | $A_{ec}$[b] |
|---|---|---|---|---|---|---|
| | | | *Mercedes Benz* | | | |
| 18.5 | 30.65 | 4.59 | 26.06 | 15.0 | 7.95 | 9.35 |
| 18.1 | 28.25 | 3.32 | 24.93 | 11.8 | 8.41 | 9.53 |
| 10.9 | 18.54 | 1.94 | 16.60 | 10.5 | 7.41 | 8.28 |
| 10.3 | 16.46 | 2.01 | 14.44 | 12.2 | 7.86 | 8.96 |
| 9.4 | 14.73 | 1.24 | 13.49 | 8.4 | 7.98 | 8.71 |
| 9.4 | 14.41 | 1.59 | 12.82 | 11.0 | 8.16 | 9.17 |
| 8.6 | 13.84 | 1.34 | 12.50 | 9.7 | 7.74 | 8.56 |
| 8.5 | 13.00 | 1.31 | 11.69 | 10.1 | 8.13 | 9.05 |
| 6.4 | 10.52 | 1.24 | 9.29 | 11.8 | 7.48 | 8.51 |
| Average | | | | 11.2 | 7.90 | 8.90 |
| | | | | ±1.9 | ±0.32 | ±0.42 |
| | | | *Volkswagen* | | | |
| 9.5 | 23.34 | 8.94 | 14.44 | 38.3 | 5.09 | 8.23 |
| 7.2 | 17.09 | 7.03 | 10.03 | 41.1 | 5.21 | 8.87 |
| 7.0 | 16.03 | 5.93 | 10.10 | 37.0 | 5.39 | 8.55 |
| 6.1 | 13.58 | 4.84 | 8.69 | 35.8 | 5.52 | 8.62 |
| 6.0 | 13.56 | 4.27 | 9.22 | 31.5 | 5.43 | 7.99 |
| 3.6 | 9.04 | 2.79 | 6.25 | 30.8 | 4.83 | 6.98 |
| Average | | | | 35.8 | 5.25 | 8.21 |
| | | | | ±4.1 | ±0.26 | ±0.68 |
| Fleet average | | | | 23.5 | 6.58 | 8.56 |

[a] $A_e$ based on total particulate mass concentration.

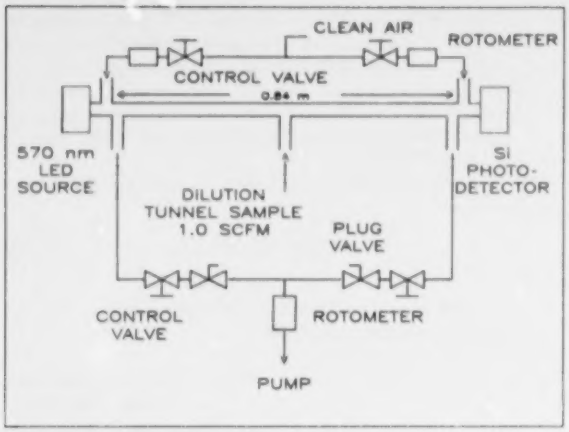


**Figure 3.** Instrument configuration for opacity determination.

air supplies were then adjusted to minimal but equal amounts. Stable air and sample flows provided excellent stability for the instrument and source/detector protection free of contamination. A typical opacimeter response to a transient driving cycle is shown in Figure 4. The fast rise of opacity during acceleration demonstrates the instrument capability for real time measurements.

After examining the continuous response, the opacimeter was further tested for its accuracy and precision in determining $C_e$ emission rates. Two diesel passenger cars were chosen for the tests: a 1980 Volkswagen Rabbit and a 1984 Mercedes Benz 300SD with significantly different particulate emissions characteristics. Full exhaust was vented into a dilution tunnel. To obtain particulate emissions with varied physical and chemical characteristics, the vehicles were operated on a chassis dynamometer over a wide range of transient speeds and loads. The relationship of opacity to particulate mass was established by comparing the integrated opacities obtained while operating the two vehicles over a variety of dynamometer transient driving schedules with gravimetric particulate masses determined using classical filtration procedures. The particulate matter was filter-collected by sampling a constant fraction of the air diluted exhaust concurrently with the opacity measurements. Pallflex Teflon-coated glass fiber filters (TX40H120WW-47mm) were used to collect the particulate matter, and methylene chloride soxhlet extraction to determine the soluble organic fraction (SOF). The residual mass on the filter after extraction was taken to represent the $C_e$ content.

Mass specific extinction coefficients listed in Table II were calculated by applying Equation 1 to individual run data. The extinction cross section per unit mass of total particles, $A_{et}$, had a fleet average of 6.58 $m^2/g$. It differed substantially between cars, having averages of 7.90 ± 0.32 $m^2/g$ and 5.25 ± 0.26 $m^2/g$ for the Mercedes and Volkswagen, respectively, primarily due to the difference in SOF content. The particulate SOF varied from 11 percent to 36 percent by weight. These vehicles were purposely selected to range the SOF as much as possible within reason for diesel engines.[25] The fleet average extinction cross section per unit mass of $C_e$, $A_{ec}$, was 8.56 $m^2/g$. This quantity was very similar for the two cars, having average values of 8.90 ± 0.42 $m^2/g$ and 8.21 ± 0.68 $m^2/g$ for the Mercedes and Volkswagen, respectively. This confirms findings by previous investigators that the extinction cross section per unit mass of elemental carbon smoke is not strongly dependent on variations in organic content in the visible region.[11,12,25]

To estimate the degree of light extinction owing to extractables, extinction cross section per unit mass total particulates, $A_{et}$, was plotted versus the $C_e$ mass fraction as shown in Figure 5. The intercept of the linear regression line provides a measure of light extinction cross section per unit mass extractables. Its small value of −1.26 $m^2/g$, when considered with the uncertainty of the measurements and linear regression model, confirms the results of previous investigations that the contribution of condensed organic matter to opacity is negligible. The value at 100 percent $C_e$ mass fraction, 8.99 $m^2/g$, represents the mass specific extinction coefficient for $C_e$. This valve is very similar to the average in Table II.

The vehicle data were further analyzed by regressing the

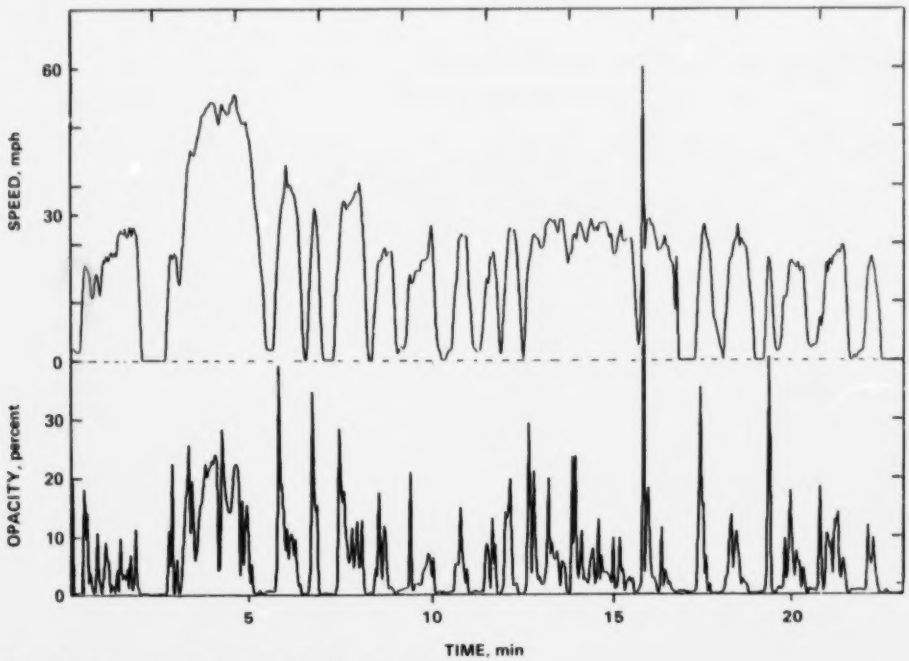


**Figure 4.** Response characteristics of opacity instrument.

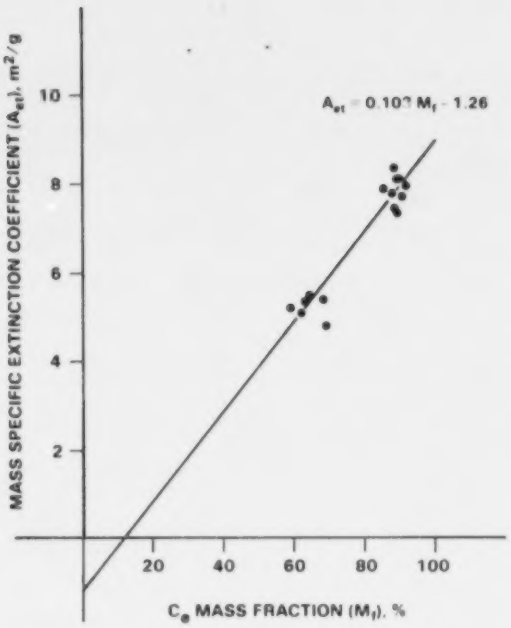


**Figure 5.** Mass specific extinction coefficient versus $C_e$ mass fraction.

measured extinction coefficients, $B_e$, against $C_e$ mass loadings, $M_c$, as shown in Figure 6.

$$B_e = A_{ec}M_c + C \qquad (2)$$

The parameter $A_{ec}$ in the above regression function represents the mass specific extinction coefficient for $C_e$. The intercept $C$ is $-0.015\ m^{-1}$. The nonzero intercept might be attributed to regression model uncertainty, background noise, and errors in the instrument and gravimetric measurement. The slope $A_{ec}$ of 9.9 $m^2/g$ can be compared to the average value 8.6 $m^2/g$ in Table II and 9.0 $m^2/g$ in Figure 5 at 100 percent $C_e$ mass fraction.

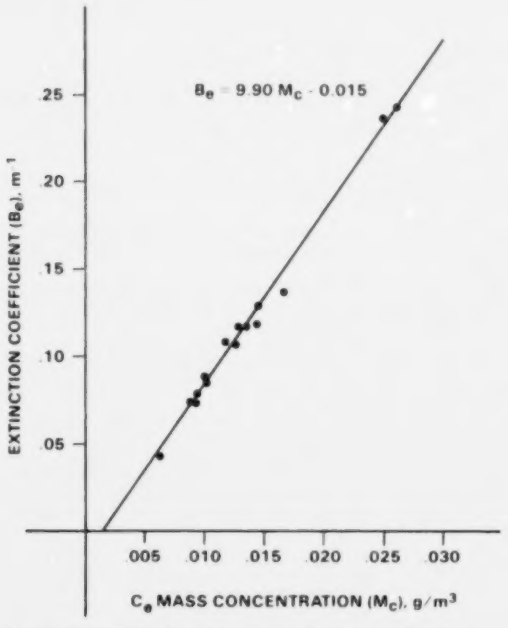


**Figure 6.** Extinction coefficient versus $C_e$ mass concentration.

There exists extensive literature on the optical properties of diesel exhaust and carbon soot. However, the wide variation in optical sources and sampling conditions employed do not allow accurate cross-comparison for statistical analyses. In Table III, a few typical works are summarized, but it is by no means complete. In the Rayleigh regime, when a particle size is relatively small compared with the wavelength of incident light, the extinction cross section is inversely proportional to the light wavelength.[24,26]

When diesel particulate emissions less than 0.1 μm are considered, extinction coefficient adjustments according to incident light wavelength is necessary for comparison of data developed at different wavelengths, and such adjustments have been made in the extinction coefficient values of Table III to a reference wavelength of 0.57 μm. Depending on the degree of particulate agglomeration, which is sensitive to dilution dynamics, this adjustment may or may not be appropriate. This adjustment has been considered in previously reported studies of diesel and ambient particulate matter.[21,27] As indicated in Table III, the values obtained from this study are very close to the average of all listed values. The listed values, $A_{ec}$, have a range from 7.5 to 9.9

**Table III.** Summary of previous light extinction measurements for elemental carbon in diesel exhaust or soot.

| Reference | $A_{ec}$ ($m_2/g$) | Light wavelength (μm) | Corrected[a] $A_{ec}$ ($m^2/g$) | Test sample |
|---|---|---|---|---|
| 11 | 9.1[b] | 0.550 | 9.4 | Diluted diesel exhaust |
| 12 | 7.5 | 0.570 | 7.5 | Diluted diesel exhaust |
| 21 | 8.9[c] | 0.633 | 8.0 | Diluted diesel exhaust |
| 25 | 9.5[d] | 0.570 | 9.5 | Raw diesel exhaust |
| 26 | 9.8 | 0.5145 | 8.8 | Acetylene soot |
| Current study | 9.0[e] | | 9.0 | Diluted diesel exhuast |
| | 9.9[f] | 0.57 | 9.9 | |
| Average | | | 8.9 ± 0.9 | |

[a] Corrected at the reference wavelength of 0.57 μm.
[b] Mass specific absorption coefficient.
[c] Calculated from reported values, $A_{et}$ of 4.9 $m^2/g$ and $C_e$ mass fraction of 0.55, respectively.
[d] Extinction cross section per unit mass total particulate.
[e] See Figure 5.
[f] See Figure 6.

with a mean and standard deviation of 8.9 and ±0.9, respectively. Hence, it may be reasonable to expect approximately 10 percent errors when an opacimeter is utilized for monitoring real-time diesel particulate $C_e$ emissions. This agrees with the observations of this study and of other investigators.[13,14]

With diluted exhaust, as examined in this study, the opacity is sufficiently low that Equation 1 can be reasonably simplified to

$$P = AM_c + C \qquad (3)$$

where $A \sim 100\ A_eL$. The parameter $C$ provides flexibility to account for the nonideal characteristics of diesel exhaust with regard to the Beer-Lambert relationship of opacity to concentration. The results of the regression are shown in Figure 7 for the combined $C_e$ data of this study. The observed multiple correlation coefficient was 0.992, with a slope $A$ of 734 and intercept $C$ of −0.51.

## Summary and Conclusion

Analytical procedures based on the flame ionization properties of organic carbon and the optical opacity or light extinction properties of elemental carbon have been evaluated for continuous measurement of diesel particulate emissions during transient engine operation. The matched differ-

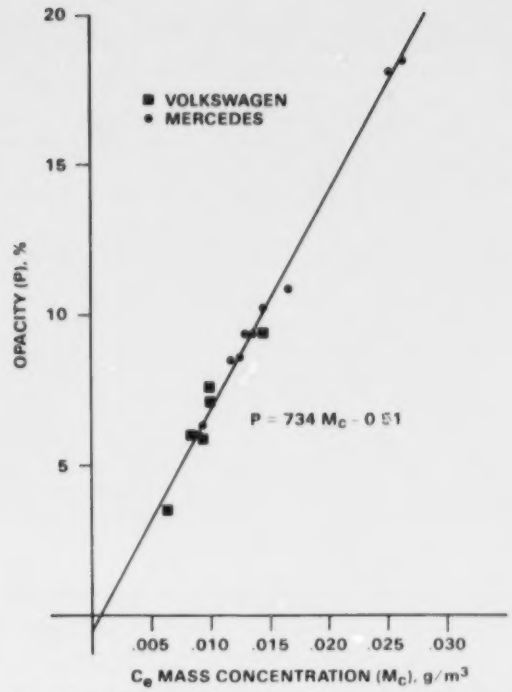


**Figure 7.** Regression of opacity and $C_e$ mass concentration measurements.

ential hot FID procedure provided a means for time resolved measurement of particulate phase organic carbon emissions. This procedure was qualified by comparison to classical gravimetric solvent extraction procedures. The ratio of FID particulate phase organic mass to gravimetric mass was 0.77, comparable to a value 0.70 observed in a previously reported study comparing thermal-optical organic analysis to solvent extraction. The opacimeter provided a means for time resolved measurement of elemental carbon emissions. The extinction cross section per unit mass of elemental carbon emissions did not differ much between tested vehicles. There was weak dependence on particulate phase organic concentrations. The representative value found in this study was 9.0 $m^2/g$, which compares favorably with the average 8.9 $m^2/g$ of other typical investigations. These measured values have a standard deviation of approximately 10 percent. It appears that a linear regression model $P = AM_c + C$ can be reasonably used to correlate opacity with $C_e$ mass at concentrations below about 0.04 $g/m^3$, having a multiple correlation coefficient of 0.992.

The described instrumentation provides adequate time resolution for continuous measurement of transient diesel particulate phase elemental and organic carbon. Future planned application of these systems will include interface to fast PC-based analogue to digital conversion and data processing systems, that will permit convenient examination of emissions characteristics during varied driving modes, e.g., acceleration, deceleration, and steady-state speed conditions, as well as during particulate trap regeneration.

## Acknowledgments

Although the research described in this article has been supported by the United States Environmental Protection Agency, it has not been subjected to Agency review. Therefore, it does not necessarily reflect the views of the Agency and no official endorsement should be inferred. The authors wish to acknowledge and express gratitude to Susan Bass for assistance in manuscript preparation.

## References

1. "Standard for emission of particulate regulation for diesel-fueled light-duty vehicles and light-duty trucks," *Federal Register* **45:** 14505, March 5, 1980.
2. "Standard for emission of particulate matter from diesel-powered light-duty vehicles and light-duty trucks and technical amendment to emission regulations for light-duty vehicles, light-duty trucks, and heavy-duty engines, final rule," *Federal Register* **49:** 3021, January 24, 1984.
3. "Particulate emission regulations for 1988 and later model year heavy-duty diesel engines," *Federal Register* **50:** 10606, March 15, 1985.
4. "Diesel Particulate Emissions Control," SP-537, Society of Automotive Engineers, Inc., Warrendale, PA, 1983.
5. "Diesel Particulate Traps," P-140, Society of Automotive Engineers, Inc., Warrendale, PA, 1984.
6. C. Weaver, "Trap-Oxidizer Technology for Light-Duty Diesel Vehicles: Status, Prospects, and Current Issues," SAE Paper 831713, 1983.
7. F. Black, J. Braddock, R. Bradow, "Highway motor vehicles as sources of atmospheric particles: projected trends 1977 to 2000," *Environ. Int.* **11:** 205 (1985).
8. S. L. Plee, J. S. McDonald, "Some Mechanisms Affecting the Mass of Diesel Exhaust Particulate Collected Following a Dilution Process," SAE Paper 800186, 1980.
9. C. E. Findley, A. T. Rossano, "Continuous Monitoring of Particulate Matter in Automobile Exhaust," presented at the 65th APCA Annual Meeting, Miami Beach, FL, 1972.
10. G. L. Green, D. Wallace, "Correlation Studies of an In-Line, Full-Flow Opacimeter," SAE Paper 801373, 1980.
11. H. C. Scherrer, D. B. Kittelson, D. F. Dolan, "Light Absorption Measurements of Diesel Particulate Matter," SAE Paper 810181, 1981.
12. S. M. Japar, A. C. Szkarlat, "Real-Time Measurements of Diesel Vehicle Exhaust Particulate Using Photoacoustic Spectroscopy and Total Light Extinction," SAE Paper 811184, 1981.
13. D. M. Roessler, "Opacity and Photocoustic Measurements of Diesel Particulate Mass Emissions," GMR-3932, General Motors Research Laboratories, Warren, MI, 1981.
14. D. H. Gerke, "Real-Time Measurement of Diesel Particulate Emissions with a Light Extinction Opacity Meter," SAE Paper 830183, 1983.
15. R. Whitby, R. Gibbs, R. Johnson, B. Hill, S. Shimpi, R. Jorgenson, "Real-Time Diesel Particulate Measurement Using a Tapered Element Oscillating Microbalance," SAE Paper 820463, 1982.
16. P. R. Shore, R. D. Cuthbertson, "Application of a Tapered Element Oscillating Microbalance to Continuous Diesel Particulate Measurement," SAE Paper 850405, 1985.
17. J. C. Clerc, J. H. Johnson, "A Computer Heat Transfer and Hydrocarbon Adsorption Model for Predicting Diesel Particulate Emissions in Dilution Tunnels," SAE Paper 821218, 1982.
18. *U.S. Code of Federal Regulations*, Title 40, Part 86—Control of Air Pollution from New Motor Vehicles and New Motor Vehicle Engines; Certification Test Procedures, Appendix I—Urban Dynamometer Schedules, 669, 1983.
19. F. M. Black, L. E. High, J. E. Sigsby, "The application of total hydrocarbon flame ionization detectors to the analysis of hydrocarbon mixtures from motor vehicles, with and without catalytic emission control," *Air, Water, Soil Pollut.* **5:** 53 (1975).
20. S. M. Japar, A. C. Szkarlat, R. A. Gorse, E. K. Heyerdahl, R. L. Johnson, R. A. Rau, J. J. Huntzicker, "Comparison of solvent extraction and thermal-optical carbon analysis methods — application to diesel vehicle exhaust aerosol," *Environ. Sci. Technol.* **18:** 231 (1984).
21. A. C. Szkarlat, S. M. Japar, "Optical and chemical properties of particle emissions from on-road vehicles," *JAPCA* **33:** 592 (1983).
22. C. T. Vuk, M. A. Jones, J. H. Johnson, "The Measurement and Analysis of the Physical Character of Diesel Particulate Emissions," SAE Paper 760131, 1976.
23. "The Physical and Chemical Character of Diesel Particulate Emissions — Measurement Techniques and Fundamental Considerations," SP-430, Society of Automotive Engineers, Inc., Warrendale, PA, 1978.
24. C. F. Bohen, D. R. Huffman, *Absorption and Scattering of Light by Small Particles*, Wiley, New York, NY, 1983.
25. D. M. Roessler, F. R. Faxvog, "Changes in diesel particulates with engine air/fuel ratio," *Comb. Sci. Technol.* **26:** 225 (1981).
26. D. M. Roessler, F. R. Faxvog, "Optical properties of agglomerated acetylene smoke particles at 0.5145-$\mu$m and 10.6-$\mu$m wavelengths," *J. Opt. Soc. Am.* **70:** 230 (1980).
27. H. Rosen, A. D. A. Hansen, T. Novakov, "Identification of the Graphitic Carbon Component of Source and Ambient Particulates by Raman Spectroscopy and an Optical Attenuation Technique," in *Proceedings, Conference on Carbonaceous Particles in the Atmosphere*, LBL-9037, Conf. 7803101, UC-11, Lawrence Berkeley Laboratory, Berkeley, CA 49–55, 1979.

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This article documents research that was conducted under the auspices of the U.S. Environmental Protection Agency (USEPA). As an arm of the government, the USEPA has a paid up, non-exclusive, irrevocable, worldwide license to reproduce, prepare derivative works, and distribute to the public all of the material contained herein, and to grant others acting on its behalf the right to do so. The USEPA grants to the National Technical Information Service, Department of Commerce, the right to act as its agent in the distribution of this material.